UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1b. RESTRICTIVE MARKINGS	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
3. DISTRIBUTION / AVAILABILITY OF REPORT	Approved for public release: Distribution Unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	AFGL-TR-88-0294
5. MONITORING ORGANIZATION REPORT NUMBER(S)	
6a. NAME OF PERFORMING ORGANIZATION	Air Force Geophysics Laboratory
6b. OFFICE SYMBOL (If applicable)	LW
6c. ADDRESS (City, State, and ZIP Code)	Hanscom AFB Massachusetts 01731-5000
7a. NAME OF MONITORING ORGANIZATION	Air Force Geophysics Laboratory (LW)
7b. ADDRESS (City, State, and ZIP Code)	Hanscom AFB Massachusetts 01731-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	
8b. OFFICE SYMBOL (If applicable)	
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)	

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
61102F	2309	G1	11

11. TITLE (Include Security Classification)
RESULTS OF A TOWER GRAVITY EXPERIMENT

12. PERSONAL AUTHOR(S) Donald H. Eckhardt, Christopher Jekeli, Andrew R. Lazarewicz, Anestis J. Romaides and Roger W. Sands

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Reprint	FROM 1Jan87 TO 31Dec87	1988 October 12	7

16. SUPPLEMENTARY NOTATION
Proceedings of the XXIIIrd RENCONTRE DE MORIOND, JANUARY 23-30, 1988

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Gravity, 5th Force, Non-Newtonian Gravity, Inverse-Square Law, Reprints.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
DONALD H. ECKHARDT	617-377-4060	AFGL/LW

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

$m_1 > m_0$

VIIIth Moriond Workshop
Les Arcs, Savoie, France - January 23-30, 1988

5th FORCE - NEUTRINO PHYSICS
Series : Moriond Workshops

ISBN 2-86332-054-8

EDITIONS FRONTIERES
B. P. 33
91192 Gif-sur-Yvette Cedex - France

Printed in Singapore by Kim Hup Lee Printing Co. Pte. Ltd.

Proceedings of the XXIIIrd RENCONTRE DE MORIOND
Series : Moriond Workshops
Les Arcs, Savoie, France — January 23-30, 1988

5th FORCE
NEUTRINO PHYSICS

edited by

O. FACKLER
and J TRAN THANH VAN

Editions Frontières

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ABSTRACT

We have performed an experimental test of Newton's inverse-square law of gravitation. The test compared gravity values measured on a 600 m tower with upward continued gravity estimates calculated from ground measurements. A significant departure from the inverse-square law was detected, asymptotically approaching -500 ± 35 μGal (1 μGal = 10^{-8} ms^{-2}) at the top of the tower; this indicates that at the base of the tower there is a non-Newtonian attractive force that falls off rapidly with elevation. The results of the experiment are marginally consistent with a one term Yukawa type attractive force, but they are fully consistent with two Yukawa type forces, attractive and repulsive, in which case they are also compatible with Airy and Cavendish experiments. The experiment provides evidence that supports the hypothesis of a spin-0 graviscalar and of a spin-1 graviphoton. The masses (~ 1 neV) and coupling constants (not well defined, but at least 3% that of the graviton, and perhaps much more) of both particles are approximately the same, but because $m_1 > m_0$, the attractive scalar field is the dominant source of the measured effect.

Preliminary results of this experiment were presented at the Rencontres de Moriond. The final results are now complete, and they have been submitted[1] to <u>Physical Review Letters</u> (PRL) for publication. This account includes some of the PRL material, including the final results.

"We were raising the lower pendulum up the South Shaft for the purpose of interchanging the two pendulums, when (from causes of which we are yet ignorant) the straw in which the pendulum-box was packed took fire, the lashings burnt away, and the pendulum with some other apparatus fell to the bottom. This terminated our operations of 1826." George Biddell Airy[2]

Evidence for non-Newtonian gravitation from gravimetric measurements (Airy experiments) in mines and boreholes is suggestive, but hardly compelling. These estimates[3] of the gravitational constant, G, are all about one per cent higher than the more precise laboratory estimates[4], but the discrepancies are just barely significant when compared with the experimental uncertainties and allowing for the possibility of unmodeled variations in regional free-air gradient anomalies and random or systematic errors in density estimates.

If there is a non-Newtonian component of gravity[5], its potential is generally assumed to be Yukawan. The gravitational potential of a point mass, m, then has the form $-G\,m r^{-1}[1+\alpha \exp(-r/\lambda)]$. For a laboratory experiment, $r/\lambda << 1$, and the Cavendish constant is $G(1+\alpha)$. For a flat earth (radius >> λ), the gravity perturbation caused by the Yukawan term is $\delta g = 2\pi G|\delta\sigma|\,\alpha\lambda\,\exp(-|\zeta|/\lambda)$, where ζ is the distance from the earth's surface and $\delta\sigma$ is the density difference across the surface. Generally, $|\zeta|/\lambda >> 1$ for the Airy experiments; not being sensitive to the δg term, they measure G. To resolve $\alpha\lambda$ and λ from measurements of δg, the Airy experiments require good measurements near a surface that is well mapped topographically and gravimetrically. Because δg is symmetrical about $\zeta = 0$, $\alpha\lambda$ and λ might also be resolved from measurements of δg above a well mapped surface. Furthermore, σ can be estimated (absolutely) more accurately for air than for rock, so the Newtonian gravity "noise" that impairs the precise determination of δg (and, in turn, $\alpha\lambda$ and λ) is negligible above the earth's surface. This was a major motivation for our tower gravity experiment.

Of the (approximately) 40 TV transmission towers that rise 600 m above local ground level in the United States, we chose the WTVD tower in Garner, NC. The tower, built in 1978 by Kline Iron and Steel of Columbia, SC, is mechanically remarkably stable; we could make reliable and repeatable gravity measurements at all tower levels when the wind speed was 3 ms^{-1} or less. The tower is in a relatively flat area of the North Carolina coastal plain, 220 km from the ocean and 350 km from the mountains. The regional geology and gravity field have been well mapped, and they are rather featureless. And, most importantly, we had the hospitality and cooperation of the WTVD management and staff[6].

At the base and at six different levels of the tower (93.90, 192.14, 283.56, 379.51, 473.21, and 562.24 m above ground level), we measured **g** with a LaCoste-Romberg (L&R) Model G gravimeter[7]; elevations were simultaneously measured with an electronic distance meter. Altogether there were 30 tower gravity observations, tied to seven base station observations through five adjustment loops. Our estimated uncertainties for the tower measurements range from 23 (lowest level) to 27 μGal (top). At 77 sites in the inner zone (within 5 km of the tower), we measured **g** with the same gravimeter, tying the measurements to the tower base station; altogether there were 257 inner zone gravity observations, with at least two per site. DMA (the U. S. Defense Mapping Agency) surveyed the inner zone site coordinates using its Inertial Positioning System and third order differential leveling. The uncertainty of each ground survey gravity measurements is about 20 μGal. From its gravity library, DMA provided gravity measurements and coordinates at numerous sites in the region; we used data from 1784 of these DMA catalogued sites for the outer zone (between 5 and 220 km of the tower). The gravity uncertainties at these outer zone sites are estimated to be about 1 mGal. The approximate relative weights of the inner and outer zones in the upward continuation estimation of **g** at the top of the tower are 95% and 5% respectively.

Geodesists and physicists usually do not speak the same technical language; indeed, their potentials have opposite signs. Many of the words, concepts and mathematical tools for analyzing the tower gravity experiment come from geodesy. A translation for physicists is required, so here it is[8]. Let **W** be the gravity potential of the earth which is the sum of a gravitational potential **V** and a centrifugal potential Φ. In cylindrical coordinates (ρ = distance from rotation axis), the centrifugal force is $-\nabla\Phi = \omega^2\rho$ where ω is the earth angular rate of rotation. Taking the divergence, $-\nabla^2\Phi = \rho^{-1}\partial(\omega^2\rho^2)/\partial\rho = 2\omega^2$, so in any coordinate system the centrifu-

gal potential satisfies $\nabla^2\Phi = -2\omega^2$. The gravitational potential satisfies Poisson's equation, $\nabla^2 V = 4\pi G\sigma$. Thus $W = V + \Phi$ satisfies

$$\nabla^2 W = 4\pi G\sigma - 2\omega^2. \quad (1)$$

In curvilinear coordinates

$$\nabla^2 W = \frac{1}{h_1 h_2 h_3} \sum_{i=1}^{3} \frac{\partial}{\partial \xi_i}\left[\frac{h_1 h_2 h_3}{h_i^2}\frac{\partial W}{\partial \xi_i}\right]. \quad (2)$$

Let $\partial W/\partial\xi_2 = \partial W/\partial\xi_3 = 0$; then $W(\xi_1) = constant$ defines an equipotential surface. This surface has the curvature $J(\xi_2, \xi_3) = \frac{1}{2}[1/h_2 + 1/h_3]$. Let $h_1 = 1$, $d\xi_1 = dH$, and $\partial W/\partial H = g$ (positive downwards). Then, from (1) and (2), using $\partial h_2/\partial H = \partial h_3/\partial H = 1$,

$$\partial g/\partial H = 4\pi G\sigma - 2gJ - 2\omega^2. \quad (3)$$

This is Bruns' equation. The second derivative of g is approximately

$$\partial^2 g/\partial H^2 \approx 6gJ^2. \quad (4)$$

In geodetic practice, W is reduced to a computationally manageable level by subtracting a reference field, U, that encompasses the central force, centrifugal and ellipsoical components; this relegates various subsequent approximations to second order. Here we let U also include the attraction of the atmosphere, which then guarantees the harmonicity of the resulting disturbing potential, $T = W - U$, above the earth's surface. A defined equipotential surface (rotating ellipsoid of revolution) completes the definition of U and of its gradient, the normal gravity, γ, at any point Q on the ellipsoid or at height H above the ellipsoid. A truncated Taylor series, using $\gamma = g$ in (3) and (4), generally suffices. The gravity anomaly, Δg, at a point P on the normal through Q is defined as the difference between gravity at P and normal gravity at Q, where $W_P = U_Q$. The height difference between P and Q is unknown, but the difference between the height of Q above the ellipsoid and the height of P above the reference equipotential surface of W,

the geoid, is negligible in non-mountainous terrain. The spherical approximation of Δg is given by $\Delta g_r = -\partial T/\partial r - 2T/r$, where r is the radial coordinate; and its flat earth approximation is $\Delta g_\zeta = -\partial T/\partial\zeta$, where ζ is the local vertical coordinate. Therefore, $r\Delta g_r$ is harmonic in a spherical coordinate system and Δg_ζ is harmonic in Cartesian and cylindrical coordinate systems. The spherical and flat earth approximations are entirely adequate for upward continuations of gravity anomalies for this experiment.

We used two methods to estimate Δg at the gravity observation levels on the tower[9]. Method I, based on the Poisson integral and least-squares collocation, upward continues the $r\Delta g_r$'s. Method II, based on the Fourier-Bessel series, upward continues the Δg_ζ's. The Δg differences between the two techniques, which are compatible with the uncertainty estimates (~20 to 50 μGal), are assuringly small: 30 μGal at the lowest level, and no more than 10 μGal at the other levels. (Errors in the Δg estimates are highly correlated between different levels and between the two methods because they use a common set of inner zone gravity samples.)

If Newton's inverse-square law is valid, g observed on the tower should agree, except for allowable error, with $\Delta g + \gamma$ modeled from surface data using either of the upward continuation methods for Δg, and using γ for g in Bruns' equation (3) and its derivative (4). The 172 mGal difference between $\Delta g + \gamma$ at the top level of the tower and at its base derives 99% from the difference in γ, and 1% from the difference in Δg. The differences, g (observed) − g (modeled), and their uncertainties (in μGal) are as follows:

Level (m)	Method I	Method II
93.90	-147±29	-117±55
192.14	-267±34	-272±49
283.56	-378±35	-384±45
379.51	-468±33	-467±39
473.21	-508±33	-501±37
562.24	-511±34	-501±35

Unless these differences are artifacts of unsuspected errors, the data indicate that at the base of the tower there is a non-Newtonian attractive gravitational force that falls off rapidly with elevation. If it is not gravitational, the effect is one that increases with elevation and gradually levels

off to a maximum in the upper reaches of the tower. We tested for possible error sources that could cause such an effect, including effects of magnetic fields, radio frequency interference, and tower motions, and found none.

A least-squares fit of $\delta g(\zeta)-\delta g(0) = 2\pi G|\delta\sigma|\alpha\lambda\,[\exp(-|\zeta|/\lambda)-1]$ to the Method II data gives $\alpha = 0.0204$ and $\lambda = 311$ m. With this model, the Airy **G** should be about two per cent lower than the Cavendish **G**, not one per cent higher. A δg due to a one term Yukawa potential cannot account for these results, but if δg is due to a two term (scalar and vector) Yukawa potential[10], it can. Let the subsripts 0 and 1 denote the scalar and vector fields respectively. Then the gravitational potential has the form $-Gmr^{-1}[1+\alpha_0\exp(-r/\lambda_0)-\alpha_1\exp(-r/\lambda_1)]$, and its corresponding gravity perturbation is $\delta g = 2\pi G|\delta\sigma|\,[\alpha_0\lambda_0\exp(-|\zeta|/\lambda_0)-\alpha_1\lambda_1\exp(-|\zeta|/\lambda_1)]$. The problem now is that we have four α, λ parameters instead of two. Reducing the number of parameters to two by setting $\alpha_1 = \alpha_0 - 0.007$ (from Airy and Cavendish experiments) and $\alpha_0\lambda_0 - \alpha_1\lambda_1 = 5.1$ m (implied by $\delta g(\zeta) - \delta g(0) \rightarrow -500\ \mu$Gal as $\zeta \rightarrow \infty$), the lower limit for α_0 is 0.03, but it has no upper limit. The λ's fall between 20 and 180 m when α_0 is small, but they are close to 100 m (mass $\approx$ 1 neV) for $\alpha_0 \approx \alpha_1 \geq 1$. Further gravimetric experiments will test the existence of the scalar-vector model and determine $\alpha_1 - \alpha_0$ more precisely, but other types of experiments[11] will be required to estimate α_0.

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